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Simulation of Broadband Antireflection Coatings at Oblique Incidence of Light

A.P. Ovcharenko[1,*], V.I. Bilozertseva[2], D.A. Gaman[2], L. Durdyeva[1]

[1] *V.N. Karazin Kharkiv National University, Svobody Sq. 4, 61022, Kharkiv, Ukraine*
[2] *National Technical University "KPI", 21 Frunze str., 61002 Kharkiv, Ukraine*

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The results of simulation of optical characteristics of antireflection coatings with continuously changing refractive index are presented. The features of enlightenment at oblique light incidence are considered. The possibilities for the simultaneous enlightenment of *S*- and *P*- polarization component of the incident light are investigated.

Keywords: Thin films, Enlightenment, Multilayer coatings.

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1. INTRODUCTION

It is known that in order to reduce the loss of light due to its reflection in the solar photovoltaic cells and other optoelectronic devices use different types of antireflective coatings. Among the materials used for broadband coatings should be noted inhomogeneous dielectric layers with specially shaped dielectric constant. Recently, interest has grown to such coatings in connection with the development of a variety of technologies for nanostructured layers creating [1] which can be considered as a non-uniform refractive index thickness distribution film. Significantly that the effective refractive index can assume a very small values.

Modeling of inhomogeneous layer is produced by replacing the smooth refractive index distribution with stepped profile and description of each layer via interference matrix. This formalism allows us to find the optical characteristics (reflection coefficients, transmission, etc.) for any multilayer coatings.

The main attention is paid to the study of the spectral dependence of the coatings reflectivity for different values of the minimum refractive index: both regular and close to unity and under changing the angle of light incidence on the system over a wide angle range [2].

The possibility of a simultaneous enlightenment for alternative states of polarization of the light, and the relationship of the total thickness of the film and its optical characteristics are considered.

2. RESULTS AND DISCUSSION

To determine the features of the spectral dependences the film with a total optical thickness of λ_0 has been chosen. It was divided into zones of equal optical thickness and linear distribution of the refractive index in the range of 1.35 to 4.0. The refractive index of the substrate $n_S = 4.0$ and air $n_0 = 1.0$ (Fig. 1).

For the interpretation of the simulation results it is necessary to keep in mind the properties of the interfaces between air the lowest n layer and air clean substrate. The angular dependence of the reflectance of these interfaces is shown in figure 2.

For ease of calculation of spectral curves the relative unit ν is used; $\nu = \lambda_0/\lambda$, λ – the current wavelength.

Figure 3 shows the spectral dependence of the reflection coefficient $R(\nu)$ when the film is split into 10 or 20 layers.

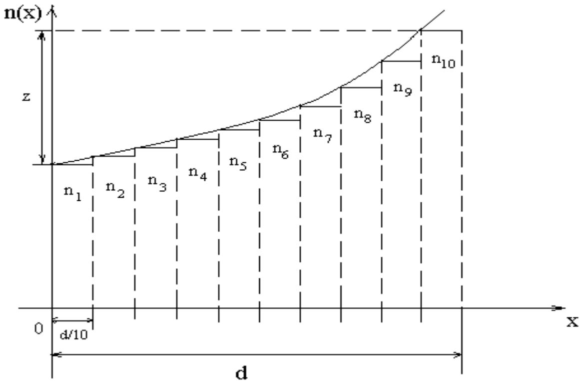

Fig. 1 – Schematic view inhomogeneous film divided into 10 zones, *d* - the optical thickness

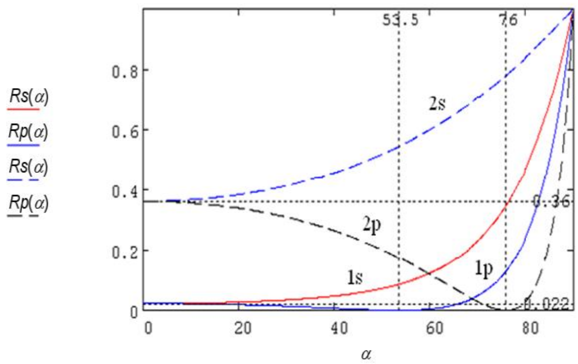

Fig. 2 – The angular dependence of the reflective coefficient of the interface for the *S*- and *P*- polarization components;
curves 1: $n_1 = 1.0$ and $n_2 = 1.35$;
curves 2: $n_1 = 1.0$ and $n_2 = 4.0$;
The dotted lines shows the value of the Brewster angle and the boundaries reflection coefficients R_0 at normal light incidence

* apovcharenko@karazin.ua

As one can see from this figure, there are the maximums on the spectral dependence of the reflection. They are located at those wavelengths for which the optical thickness of each layer is equal to or a multiple of a half wave. At these values of ν (and also $\nu = 0$) the interference matrix for each layer and the entire film matrix is equal to unit, and the reflection coefficient is equal to the reflection coefficient of border substrate-air (see. Fig. 2) $R = ((n_0 - n_S)/(n_0 + n_S))^2$.

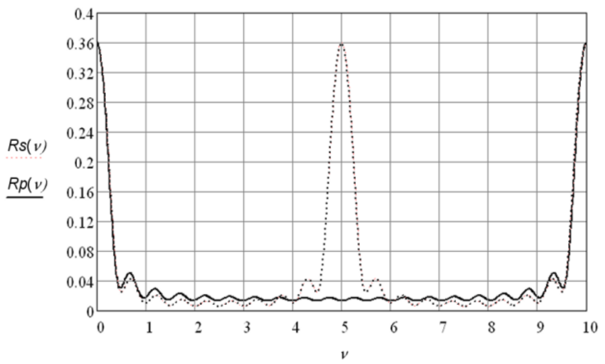

Fig. 3 – The spectra of the reflection coefficient of the film, consisting of 10 (dotted line) and 20 (solid line) layers with a linear refractive index distribution

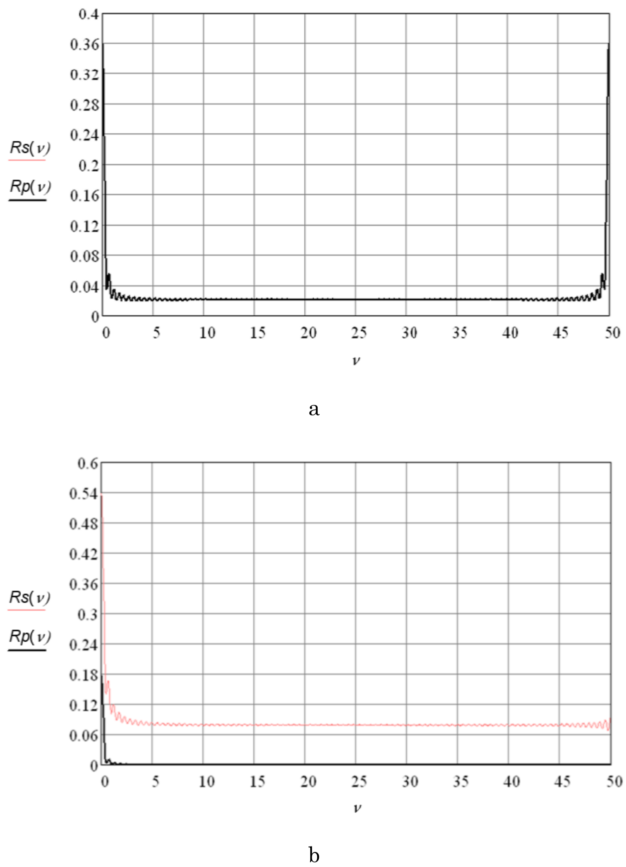

Fig. 4 – The spectral dependence of the reflection coefficient for *S*- and *P*- polarization components for film consisting of 100 layers with a linear refractive index distribution;
a - under normal light incidence;
b - under light incidence angle 53 °

A further increase of partitions number leads to both a reduction of the oscillations of $R(\nu)$, and increase of spectral range free of major peaks (see. Fig. 4a).

At oblique incidence of light (see. Fig. 4b) spectral dependence $R(\nu)$ splits into two, R_S and R_P, corresponding *S*- and *P*- polarization component of the incident light. With increasing angle of incidence R_S increases continuously and R_P decreases, reaching a minimum (in this case, practically zero) when the angle light incidence corresponding to the Brewster angle for the layer that borders on air (see the values in Fig. 2).

From a comparison of Figures 2 and 4b, it is seen that the spectral dependence of R_S and R_P "oscillate" around the corresponding values of R, determined by the minimal, bordering with air, refractive index in inhomogeneous film (in this case $n = 1.35$).

Thus, for further reducing the reflection coefficient in a wide spectral region and at oblique light incidence it is necessary to reduce used minimal refractive index.

It is interesting look at the effect of layers with ultra-low refractive index on optical characteristics of already considered coatings. Figure 5a shows the spectral dependence of $R(\nu)$ of the film containing 20 layers (same as in Fig. 3) and the same film containing an additional 21st layer with freely chosen refractive index $n = 1.1$ and an optical thickness equal to the optical thickness of the other layers. As the figure shows, the additional layer resulted in a decrease of reflectance over the entire range of wavelengths between the peaks of reflection.

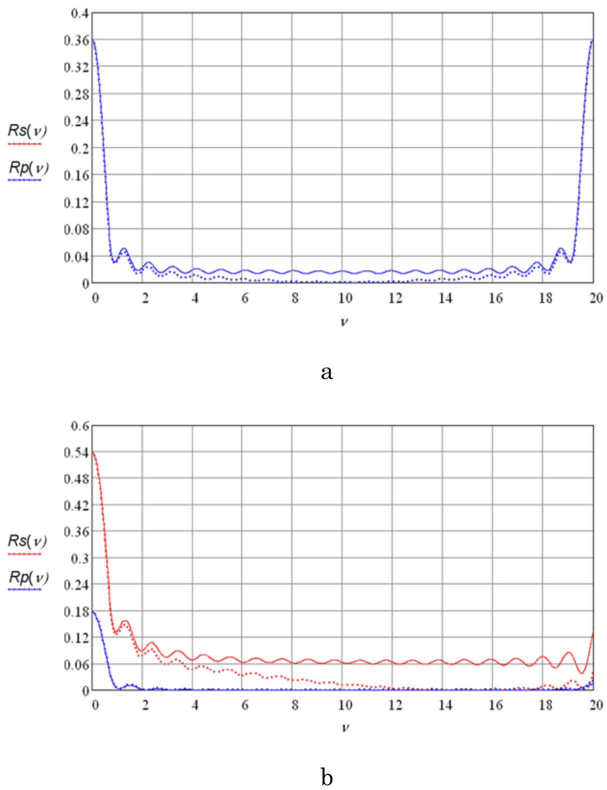

Fig. 5 – Spectral dependence of $R(\nu)$ for the film containing 20 layers (solid line), and the same film containing an additional 21st layer with a refractive index $n = 1.1$ and an optical thickness equal to the optical thickness of the other layers (dotted line);
a - under normal light incidence;
b - under light incidence angle 53 °

At oblique incidence of light (Fig. 5b), the presence of this additional layer also leads to a simultaneous enlightenment of *S*- and *P*- polarization components in a certain region of the spectrum. Variation of thickness of the additional layer allows one to shift the area of simultaneous enlightenment of the *S*- and *P*- polarization components along the spectrum.

3. CONCLUSIONS

Thus, the possibility of a simultaneous enlightenment for *S*- and *P*- polarization components of the incident light in a broad band of wavelengths by applying antireflection coatings with a smoothly varying refractive index is shown.

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